FIBER BRAGG GRATING INTERFEROMETERS FOR CHROMATIC DISPERSION COMPENSATION

FIELD OF THE INVENTION

The present invention relates to optical communication systems and more particularly concerns the compensation of chromatic dispersion in such systems.

BACKGROUND OF THE INVENTION

The present invention addresses the compensation of chromatic dispersion in optical communication systems. Chromatic dispersion designates the spectral dependence of the group velocity of light propagating along an optical fiber link [1,2]. It produces a distortion and lengthening of light pulses propagating along an optical fiber, which can eventually result in the overlap of neighboring pulses. This limits the distance over which an optical signal can be transmitted and maintained in a detectable form without reshaping. It is especially troublesome in high bit rate systems, since the distortion of the optical signal resulting from chromatic dispersion scales as the square of the signal bandwidth. Chromatic dispersion is a major limiting factor in 10 and 40 Gb/s systems.

Various chromatic dispersion compensation techniques have been devised and are reviewed in Chapter 9 of [2]. Dispersion compensation is still a field of active research, aimed at improving performances and tunability and reducing costs [3-16]. A notable advance has been the achievement of multi-channel dispersion over up to thirty-two channels using superposed fiber Bragg gratings [16,17]. This approach allows adjusting individually the dispersion level over each channel, rendering

possible the compensation of the dispersion slope as well. Gires-Tournois interferometers are also suitable as multi-channel dispersion compensators, since their spectral response is naturally periodic with regards to the optical frequency. The Gires-Tournois interferometer is a Fabry-Perot interferometer with a totally reflective back mirror that was devised from the start as a dispersion compensator [18]. Except for intra-cavity losses, the Gires-Tournois interferometer totally reflects light at all wavelengths. However, it modulates the phase of the reflected light periodically with the optical frequency. As a result, the group delay is modulated periodically as well, photons at resonant (anti-resonant) optical frequencies making the most (least) round trips inside the cavity. The same group delay curve, and hence dispersion, can be applied over the spectral bandwidth of each channel when the spectral period of the interferometer, known as the free spectral range (FSR), equals the channel frequency spacing.

The Gires-Tournois interferometer was first used to compress laser pulses or compensate for the dispersion inside ultra-short pulse lasers [19-23]. Numerical simulations showed that dispersion compensation with such an interferometer could double the transmission distance of 8 Gb/s signals over an optical fiber link [24,25]. These simulations were followed by experiments that led to improvements in the transmission of optical signals at rates of 5 and 8 Gb/s [26,27]. Following this, Dilwali and Soundra Pandian evaluated theoretically the optical fiber ring resonator for dispersion compensation [28]. This resonator behaves similarly as the Gires-Tournois interferometer but operates in transmission rather than in reflection. Finally, Ouellette *et al.* compared the Gires-Tournois interferometer to the chirped fiber Bragg grating for dispersion compensation [29]. Their analysis underlined the limited capacity of the interferometer to provide a sizable and constant dispersion over a large signal bandwidth.

The dispersion that can be achieved over a given bandwidth can be increased by cascading interferometers or by using multi-cavity interferometers [30-33]. This

observation renewed the interest in the Gires-Tournois interferometer for dispersion compensation. A cascade of interferometers or a multi-cavity interferometer preserves the spectral periodic behavior of each individual cavity as long as all cavities have the same FSR. They thus remain suitable for a multi-channel operation, while providing a level of dispersion that scales roughly as the number of cavities involved [31,33]. Design parameters that can be adjusted to obtain a desired dispersion response are the number of cavities, the reflectivity of the mirrors (other than the totally reflective back mirrors), and the optical phase angle associated with a round trip inside each cavity. The design of a cascade of single-cavity interferometers is rather straightforward, the overall dispersion then being simply the sum of the dispersion of each individual interferometer [34]. The design of a multi-cavity interferometer is more involved because all cavities must be considered as a whole. It can rely on digital filter design techniques [30,31,35,36].

Dispersion compensation by a cascade of interferometers has been demonstrated using ring cavities [3,32-34,37-39] and micro-electromechanical (MEMS) Gires-Tournois interferometers [3,34,40,41]. Ring cavities present important limitations. Increasing the FSR requires a concomitant decrease in the ring radius. For example, a 50 GHz FSR requires a ring radius smaller than 1 mm. Small ring radii can result in intra-cavity optical losses [38]. The birefringence of small radius rings also produces a strong polarization mode dispersion (PMD), that must be avoided by using light polarized along a principal axis of the rings.

Dispersion compensation by multi-cavity interferometers has been demonstrated experimentally as well. Jablonski *et al.* have developed thin-film-based two-cavity Gires-Tournois interferometers to compensate for the dispersion slope in very high bit rate optical time-domain multiplexing (OTDM) systems [42-48]. The thinness of their cavities translated into very large FSRs (many THz). Bulk multi-cavity interferometers made of a stack of thin-film-coated silica substrates have also

been used for dispersion compensation [4,5]. The substrate thickness was adjusted to produce FSRs that matched system channel spacings (50, 100 and 200 GHz).

A highly desirable feature for a dispersion compensator is tunability. The dispersion of a cascade of interferometers can be adjusted by varying the front mirror reflectivity of each interferometer as well as the optical phase angle associated with a roundtrip inside each of said interferometer. Both parameters could be adjusted within the MEMS interferometers used by Madsen *et al.* [40,41]. Each interferometer comprised a silicon substrate supporting a thin membrane whose position was controlled with an electrical voltage. The combination of this membrane and the top surface of the silicon substrate acted, through a Fabry-Perot effect, as a mirror with a reflectivity that could be adjusted electrically from 0 to 70%. The interferometer was completed by a highly reflective coating deposited on the bottom surface of the silicon substrate. The thickness of the substrate translated into a FSR of 100 GHz. The optical phase angle of the cavity was adjusted thermo-optically with a thermoelectric element controlling the temperature of the substrate. With a cascade of two such interferometers, the dispersion over a useful bandwidth of 50 GHz could be adjusted from -102 to +109 ps/nm. Two approaches have been used to adjust the dispersion of a cascade of ring cavities. In both cases, the optical phase around each cavity was adjusted thermally. Horst *et al.* used couplers that could be adjusted thermally as well [38]. Madsen *et al.* replaced each coupler by a Mach-Zehnder interferometer [3,34,37,39]. The coupling to each cavity was then varied by changing the temperature of one arm of the interferometer associated to it. The dispersion of a cascade of four such ring cavities could be varied from –1980 to +1960 ps/nm over a passband of 13.8 GHz corresponding to 60% of the FSR (23 GHz) of the device.

Jablonski *et al.* have used a variety of methods to adjust the dispersion of their multi-cavity device. Dispersion tunability was afforded, for example, by a variable thickness air gap [43,47] or by profiled thin film layers [44,45]. Dispersion

was also varied by changing the number of reflections undergone by an optical signal zigzagging between two dispersion compensators [46,48].

The principle of operation of the dispersion compensator presented by Moss *et al.* ensures tunability [4,5]. Their compensator comprises two multi-cavity interferometers, each interferometer providing a dispersion that varies linearly over a given bandwidth. The dispersion slopes of the interferometers are equal in magnitude but of opposite signs. The dispersion resulting from cascading the two interferometers is proportional to the spectral shift between them, which is controlled thermally. This approach also applies when dispersion slopes are in a simple ratio. For example, a type A interferometer can be cascaded with two type B interferometers given that the dispersion slope of the latter is twice as small in magnitude.

A Gires-Tournois interferometer has a periodic spectral response and thus provides the same dispersion over all channels separated in frequency by the FSR of said interferometer. The interferometer does not provide compensation for the dispersion slope per se. Slope compensation has been built into the dispersion response of an interferometer as follows. Madsen *et al.* replaced the coupler to a ring cavity by an asymmetric Mach-Zehnder interferometer with arms of different lengths [37]. The asymmetric interferometer provides a coupling that varies slowly with wavelength. As a result, the ring cavity produces a dispersion that varies slowly from channel to channel. A similar behavior has been obtained by Moss *et al.* through the use of a vernier effect [4,5]. As aforementioned, the dispersion in their compensator results from a spectral shift between two interferometers with linearly varying dispersions of opposite slopes. To obtain dispersion slope compensation, two interferometers with slightly different FSRs are used. The slight mismatch in FSRs produces a gradual shift between successive periods of the spectral response of the first interferometer with regards to corresponding periods of the second

interferometer. This gradual shift translates into a dispersion level changing from channel to channel.

A number of patents are related to the compensation of dispersion with Gires-Tournois interferometers. Some are concerned with the tunable compensation of dispersion within ultra-short pulse lasers [49-51]. Patents [52-54] disclose thin film structures that can be regarded as multi-cavity interferometers, developed also for laser applications. These inventions do not provide dispersion levels compatible with telecommunications applications. Patent [55] addresses the compensation of dispersion in an optical communication link with a Gires-Tournois interferometer. The cavity length of the interferometer could be adjusted to optimize the dispersion compensation. Patent [56] discloses an adjustable Gires-Tournois dispersion compensator in which light transmitted by the highly reflective back mirror is used to monitor the state of the compensation. Patent [57] discloses the use of a cascade of interferometers or of multi-cavity interferometers for the compensation of dispersion. Configurations operating in transmission (ring cavities) and reflection (Gires-Tournois interferometers) are both disclosed. Patent [58] discloses a dispersion compensator based on a Gires-Tournois interferometer, either single or multi-cavity, into which light is launched at an angle. The light can thus be made to enter and exit the device at separate points. The launch angle can also be adjusted to fine tune the FSR of the interferometer. A Gires-Tournois dispersion compensator operated with an oblique incidence of light is also disclosed in patent [59]. The optical path length of the cavity can be adjusted either with a tilted glass plate or a piezo-electric element. This patent also discloses the use of a cascade of such interferometers to increase the achievable dispersion levels. Patent [60], emanating from the same original application as patent [58], also discloses a Gires-Tournois dispersion compensator. Jablonski *et al.* have deposited two patent applications disclosing their dispersion compensator [61,62]. A variety of geometries are presented to achieve multiple reflections on two thin-film based multi-cavity Gires-Tournois interferometers facing one another. The tunable dispersion compensator presented in [4,5] has been

disclosed also in patent application [63]. The invention disclosed therein includes polarization optics to shift laterally an optical beam, in order to achieve multiple reflections at a normal incidence on each multi-cavity Gires-Tournois bulk interferometers and hence increase the achievable dispersion levels.

A fiber Bragg grating consists in a quasi-periodic modulation of the index of refraction along the core of an optical fiber [64,65]. It is created by exposing a photosensitive fiber to a properly shaped intensity pattern of ultraviolet light. This light produces a permanent change in the index of refraction in selected sections of the optical fiber. The resulting optical fiber grating behaves as a wavelength-selective reflector having a characteristic reflectance spectral response. The wavelength of light that is reflected by the grating is called the Bragg wavelength. More or less complex spectral responses can be obtained by properly tailoring the refractive index modulation along the optical fiber. Their stability and reliability, in conjunction with their all-guided-wave nature, have made fiber Bragg gratings ideal candidates for fiber optic system applications. They are now used extensively in the field of optical telecommunications, e.g. for wavelength division multiplexing (WDM), for compensating chromatic dispersion in optical fibers, for stabilizing and flattening the gain of optical amplifiers and for stabilizing the frequency of semiconductor lasers.

The first fiber Bragg grating Fabry-Perot interferometer was realized in 1992 [66]. It was made of two narrow band (0.3 nm) gratings with a constant period. The gratings were separated by 10 cm, leading to a 1 GHz FSR. Following this, wide band (150 nm) interferometers were demonstrated using chirped fiber Bragg gratings [67]. A low finesse interferometer with a FSR approaching 200 GHZ was demonstrated with partially overlapping gratings. More recently, an interferometer with a FSR of 100 GHz and a finesse of up to 16 was obtained similarly with overlapping chirped fiber Bragg gratings [68].

The realization of a wide band fiber interferometer with a FSR on the order of 50-200 GHz requires some overlapping of the chirped gratings found therein, because said gratings are longer than the required cavity length (0.5-2 mm). The successful operation of these interferometers relies on the fact that interference between overlapping Bragg gratings occurs only between those points at which said gratings have the same local Bragg wavelength. This fact was demonstrated in references [16,17], where up to 16 gratings with different Bragg wavelengths were superposed in a dispersion compensator, each grating compensating for the dispersion over a single channel as expected. Dispersion compensation with fiber Bragg grating interferometers has not been reported yet. Moreover, it has not been generally recognized that wide band interferometers with FSRs of interest (50-200 GHz) could be produced using overlapping Bragg gratings. For example, it is stated in patent application [69] that : "Cavities are formed in the optical fiber between fiber Bragg grating reflectors. However a multi-cavity filter in fiber has a limited free spectral range (FSR) insufficient for a telecommunications system. For a typical 100 GHz FSR required in the telecommunications industry, the cavity length is about 1 mm. A Bragg grating reflector, if manufactured using commonly available grating-writing techniques, would need to be longer than 1 mm, and hence the two reflector cavity structure would be too long to achieve the necessary FSR."

SUMMARY OF THE INVENTION

The present invention relies on the use of Gires-Tournois interferometers for chromatic dispersion compensation. The interferometers are designed to produce a chromatic dispersion opposite that of an optical fiber link carrying an optical signal. More specifically, the disclosed interferometers are made of fiber Bragg gratings. In the present instance, the fiber Bragg gratings act as the reflectors of all-fiber Gires-Tournois interferometers.

In accordance with one aspect of the present invention, the interferometers are made of chirped gratings with a wide band reflectivity response. Overlapping gratings allows producing cavities short enough to obtain FSRs (50-200 GHz) that match the channel spacing of optical communications systems.

In one embodiment of the invention, there is provided a Fiber Bragg Grating interferometer embedded in an optical fiber for a chromatic dispersion compensation of an optical signal. The FBG interferometer is provided with a first and a second overlapping gratings, each having an identical predetermined chirp rate and a wide band reflectivity response. The first grating has a first refractive index modulation for providing a substantially total reflectivity of said first grating. The second grating has a second refractive index modulation being lower than said first one for providing a partial reflectivity of said second grating. Said gratings are longitudinally shifted from one another by a predetermined distance L, thereby defining a Fiber Bragg Grating Gires-Tournois interferometer cavity therebetween for providing the chromatic dispersion compensation of the optical signal.

In a further embodiment, the Fiber Bragg Grating interferometer is provided with a third overlapping grating having a wide band reflectivity response and the same predetermined chirp rate than said first and second gratings. The third grating is longitudinally shifted by the same predetermined distance L relatively to the second grating for defining a second cavity between said second and third gratings, thereby providing a multi-cavity FBG Gires-Tournois interferometer. The Fiber Bragg Grating interferometer may advantageously be further provided with a plurality of additional shifted overlapping gratings defining a plurality of additional cavities longitudinally distributed with the first and second cavities along the optical fiber.

In another embodiment of the present invention, there is provided an optical system for a chromatic dispersion compensation of an optical signal comprising a

plurality of FBG interferometers. Each of the FBG interferometers is provided with a first and a second overlapping gratings, each having an identical predetermined chirp rate and a wide band reflectivity response. The first grating has a first refractive index modulation for providing a substantially total reflectivity of said first grating. The second grating has a second refractive index modulation being lower than said first one for providing a partial reflectivity of said second grating. Said gratings are longitudinally shifted from one another by a predetermined distance L, thereby defining a Fiber Bragg Grating Gires-Tournois interferometer cavity therebetween. The optical system is also provided with coupling means for cascading the plurality of FBG interferometers. The coupling means has an input port for receiving the optical signal and an output port for outputting said optical signal after successive reflections through each of the plurality of FBG interferometers, thereby providing the chromatic dispersion compensation of the optical signal.

In another embodiment of the present invention, there is also provided a Fiber Bragg Grating based dispersion compensator. The FBG based dispersion compensator is provided with a multi-cavity Fiber Bragg Grating interferometer. The multi-cavity FBG interferometer comprises a first, a second and a third overlapping gratings. Each of the gratings has an identical predetermined chirp rate and a wide band reflectivity response. The first grating has a first refractive index modulation for providing a substantially total reflectivity of said first grating. Each of the second and third gratings respectively has a second and a third refractive index modulation being lower than said first one for providing a partial reflectivity of each of said gratings. The second grating is longitudinally shifted in a defined direction by a predetermined distance L relatively to the first grating for defining a first cavity between said first and second gratings. The third grating is longitudinally shifted in the same defined direction by the same distance L relatively to the second grating for defining a second cavity between said second and third gratings, thereby providing a multi-cavity FBG Gires-Tournois interferometer. The FBG based dispersion compensator is also provided with coupling means operationally connected to the multi-cavity FBG

interferometer. The coupling means has an input port for receiving an optical signal and an output port for outputting said optical signal after a reflection thereof through the multi-cavity FBG interferometer, thereby providing a chromatic dispersion compensation of said optical signal.

In a further embodiment, the FBG based dispersion compensator is also provided with a second multi-cavity FBG interferometer operationally connected to the coupling means. The dispersion compensator is also provided with two temperature controlling means, each being operationally connected to one of the FBG interferometers for thermo-optically shifting a spectral response thereof, thereby providing a tunable dispersion compensation.

The all fiber construction of the interferometers described therein ensures compactness and an increased stability and robustness in comparison to bulk interferometers.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other objects and advantages of the invention will become apparent upon reading the detailed description thereof and upon referring to the drawings in which :

FIG. 1 is a schematic representation of a single-cavity fiber Bragg grating Gires-Tournois interferometer according to a preferred embodiment of the present invention.

FIG. 2 is a schematic representation of a multi-cavity fiber Bragg grating Gires-Tournois interferometer according to another preferred embodiment of the present invention.

FIG. 3 is a graph of the spectral variation of the group delay of a single-cavity Gires-Tournois interferometer.

FIG. 4 is a graph of the linear group delay of an ideal dispersion compensator.

FIG. 5 is a schematic representation of a cascade of two single-cavity Gires-Tournois interferometers according to another preferred embodiment of the present invention.

FIG. 6 is a schematic representation of a dispersion compensator with a multi-cavity Gires-Tournois interferometer according to another preferred embodiment of the present invention.

FIG. 7 is a schematic representation of a tunable dispersion compensator with multi-cavity Gires-Tournois interferometers according to another preferred embodiment of the present invention.

FIG. 8 illustrates the principle of operation of a tunable dispersion compensator based on a pair of multi-cavity Gires-Tournois interferometers (PRIOR ART).

FIG. 9 illustrates the principle of operation of a tunable dispersion compensator with a dispersion adjustment range centered around a non-zero dispersion according to another preferred embodiment of the present invention.

FIG. 10 illustrates a dispersion slope compensation with a vernier effect (PRIOR ART).

While the invention will be described in conjunction with an example embodiment, it will be understood that it is not intended to limit the scope of the invention to such embodiment. On the contrary, it is intended to cover all alternatives, modifications and equivalents as may be included as defined by the appended claims.

DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

In the following description, similar features in the drawings have been given similar reference numerals and in order to simplify the figures, some elements are not referred to in some figures if they were already identified in a preceding figure.

The present invention concerns all-fiber Gires-Tournois interferometers for dispersion compensation. With reference to FIGURE 1, the present invention provides a Fiber Bragg Grating interferometer **30** embedded in an optical fiber **10** for a chromatic dispersion compensation of an optical signal. The FBG interferometer comprises a first and a second overlapping gratings **13**, **14** written in the core **12** of the optical fiber **10**. The two gratings **13, 14** can also extend inside the cladding **11** of the optical fiber **10** to avoid cladding mode losses. (The lateral extent of the index modulations **13** and **14** is limited by the lateral extent of the photosensitivity area of the optical fiber **10**.) Each of the gratings **13, 14** has an identical predetermined chirp rate, as illustrated by the varying period of the index modulations. Each of the gratings **13**, **14** also has a wide band reflectivity response, which can be identical or not. The first grating **13** has a first refractive index modulation, illustrated by thick lines, for providing a substantially total reflectivity of said first grating **13**. It is to be understood that such first refractive index modulation is strong enough to produce a reflectivity of the grating approaching 100%. Thus, throughout the present description, the expression "substantially total reflectivity" is intended to cover a reflectivity approaching 100%. The second grating **14** has a second refractive index modulation, illustrated by thin lines, being lower than said first one for providing a partial reflectivity of said second grating **14**. Said gratings **13**, **14** are longitudinally shifted from one another by a predetermined distance L along the fiber core **12**, thereby defining a Fiber Bragg Grating Gires-Tournois interferometer cavity therebetween for providing the chromatic dispersion compensation of the optical signal. The distance L determines the Gires-Tournois cavity length. The FSR of the

FBG interferometer **30** is determined by the distance L and the group velocity of the fundamental mode of the optical fiber **10**. Typically, a cavity length L of about 1 mm will lead to a FSR of about 100 GHz. Current and contemplated communication systems require a FSR ranging from 12.5 to 200 GHz, corresponding to a cavity length ranging from about 0.5 to 8 mm. Light propagating in the fiber core **12** from side A is essentially totally reflected by the gratings **13**, **14**, but undergoes a group delay that varies periodically with the optical frequency.

The FBG interferometer can also be provided with more gratings in order to provide a multi-cavity FBG Gires-Tournois interferometer. Thus, referring now to FIGURE 2, there is shown a FBG interferometer **50** as previously described and being further provided with a third overlapping grating **15** having a wide band reflectivity response and the same predetermined chirp rate than the first and second gratings **13**, **14**. The third grating **15** is longitudinally shifted by the same predetermined distance L relatively to the second grating **14** for defining a second cavity between the second and third gratings **14**, **15**, thereby providing a multi-cavity FBG Gires-Tournois interferometer. Thus, the length of the cavity defined by gratings **14** and **15** is the same as the length of the cavity defined by gratings **13** and **14**. This ensures that the multi-cavity interferometer **50** still has a periodical spectral response with the same FSR as determined by distance L. The index modulation of grating **15**, illustrated by dotted lines, produces a partial reflectivity. As with the single-cavity interferometer, light propagating in the fiber core from side A is totally reflected by the gratings, but undergoes a group delay that varies periodically with the optical frequency. The periodical variation of the group delay is however different from that obtained with the single-cavity interferometer. It depends on the reflectivity of each grating and on the optical phase associated with a round trip inside each of the cavities defined by gratings **13** and **14** and gratings **14** and **15**. The illustrated interferometer has three reflectors **13**, **14**, **15** and two cavities and thus represents the simplest form of a multi-cavity interferometer. It is understood that more gratings can be added in order to increase the number of cavities inside the interferometer.

Thus, in another preferred embodiment which is not illustrated, the FBG interferometer is further provided with a plurality of additional shifted overlapping gratings defining a plurality of additional cavities longitudinally distributed with the first and second cavities along the optical fiber **10**.

These fiber Bragg grating interferometers can be used in a variety of ways to achieve dispersion compensation, as exemplified in embodiments described below. Gratings can be written with appropriately polarized UV beams in order to minimize birefringence effects [68]. Fiber Bragg grating interferometers thus avoid detrimental birefringence effects associated with small ring cavities, the latter being usable only with polarized light. The possibility of writing many overlapping gratings provides more flexibility for the design and fabrication of multi-cavity interferometers with desired dispersion properties. Their all fiber construction also ensures compactness and an increased stability and robustness in comparison to bulk interferometers.

Referring now to FIGURE 3, there is shown the periodical variation of the group delay with respect to the optical frequency of a single-cavity Gires-Tournois interferometer. As can be seen, the variation of the group delay over a spectral period is highly nonlinear. This limits drastically the dispersion levels that are achievable with a single-cavity Gires-Tournois interferometer over a given bandwidth. An ideal dispersion compensator would rather produce a linear group delay as illustrated in FIGURE 4.

A linear group delay response can be approximated by cascading single-cavity Gires-Tournois interferometers, as shown for example in reference [34]. A practical implementation of this approach with fiber Bragg grating interferometers is illustrated in FIGURE 5. More particularly, the illustrated embodiment is provided with two single cavity Gires-Tournois interferometers **30a** and **30b** as described above. Of course, it is to be understood that a plurality of interferometers could also be

cascaded. The illustrated optical system is also provided with coupling means for cascading the FBG interferometers **30a** and **30b**. The coupling means has an input port **41** for receiving the optical signal and an output port **42** for outputting the optical signal after successive reflections through each of the FBG interferometers **30a, 30b**, thereby providing the chromatic dispersion compensation of the optical signal. The coupling means is preferably a circulator **40** having a plurality of intermediate ports **43**, **44**. Each of the intermediate ports **43**, **44** receives one of the FBG interferometers **30a, 30b**. The coupling means may also be a series of couplers or any other convenient means. In FIGURE 5, a four-port circulator **40** having an input port **41**, an output port **42** and two intermediate ports **43** and **44** is used. Two single-cavity Gires-Tournois interferometers **30a** and **30b** with the same FSR are located in the intermediate ports **43** and **44**. Light enters the circulator **40** by input port **41**, is then successively reflected by interferometers **30a** and **30b** and exits the circulator **40** by the output port **42**. It is understood that using an N-port circulator instead allows cascading N-2 interferometers. Preferably, the temperature of each interferometer is controlled with appropriate means. Thus, each of the interferometers **30a** and **30b** is advantageously provided with a temperature controlling means operationally connected thereto in order to thermo-optically shift the spectral response of each interferometer **30a**, **30b**. Preferably, the temperature controlling means are thermo-electric cooler but any other appropriate means could also be envisaged. The mostly linear group delay response is obtained by properly positioning the spectral responses of the interferometers with regards to one another.

One advantage of chirped Bragg gratings is the easiness in controlling their reflectivity. By varying the strength of the index modulation along the fiber, it is very simple to produce such gratings with a reflectivity that depends on wavelength in a predetermined fashion. A cascade of interferometers made of fiber Bragg gratings with spectrally dependent reflectivities can be fabricated. Such a cascade will produce a dispersion that varies from channel to channel, thus allowing the compensation of the dispersion slope as well.

The dispersion achievable over a given bandwidth can also be increased by using a multi-cavity Gires-Tournois interferometer **50** and a coupling means connected thereto, as illustrated in FIGURE 6. Preferably, the coupling means is a three-port circulator **40**. Light enters the circulator **40** via input port **41,** is then reflected by multi-cavity Gires-Tournois interferometer **50** located in intermediate port **43** and then leaves the circulator via output port **42**. Means other than a circulator, such as a coupler for example, can be used to extract the light reflected by the interferometer **50**. Advantageously, the temperature of the multi-cavity interferometer **50** is controlled by temperature controlling means, such as a thermoelectric cooler, in order to align the periods of its spectral response with transmission channels. The multi-cavity interferometer is designed to produce a group delay response approximating the linear response illustrated in FIGURE 4. The design parameters to this end are the number of cavities, equal to the number of gratings other than the highly reflective one, the reflectivity of the gratings other than the highly reflective one, and the relative optical phase associated with a roundtrip inside the cavities defined by neighboring gratings. The possibility of writing many overlapping gratings, demonstrated for example in reference [16,17], provides more flexibility in approximating a linear group delay over a sizable fraction of each period of the spectral response of the interferometer. During fabrication, two physical parameters can be used to control the relative optical phase of the cavities, i.e. the distance between the gratings and the average refractive index distribution along the fiber. The distance between the gratings can be controlled by writing them successively and changing between each the relative position of the optical fiber and the phase mask used to write said gratings with a sub-wavelength accuracy motion stage. The gratings can also be written simultaneously using a complex phase mask that predefines their relative positions. Once the gratings have been written, UV-exposure can be used to slightly modify the index of refraction of the fiber, a technique known as UV-trimming. Changing the refractive index of the optical fiber changes the optical phase of light propagating through it. UV-trimming is a well established technique in

the field of fiber Bragg gratings. This technique of course applies only to materials that are photosensitive, such as the optical fibers used to fabricate FBGs.

A tunable dispersion compensator can be fabricated using a pair of multi-cavity interferometers as disclosed in patent application [63]. A fiber Bragg grating implementation of this approach is illustrated in FIGURE 7. The set-up is the same as for a cascade of two single-cavity interferometers illustrated in FIGURE 5, except that the single-cavity interferometers **30a** and **30b** have been replaced by multi-cavity interferometers **50a** and **50b**. Multi-cavity interferometers **50a** and **50b** have the same FSR. They produce over each period of their spectral response a dispersion that varies linearly, their dispersion slopes being equal in absolute value but of opposite signs. The temperature of both interferometers **50a** and **50b** is controlled by appropriate means, such as thermoelectric coolers, as a non-limitative example, in order to vary the spectral shift between the two.

The principle of operation of such a dispersion compensator is illustrated in FIGURE 8. Graphs on the left represent the group delay of the interferometers while those on the right represent their dispersions. These graphs are representative of an ideal case where the group delay of each interferometer is parabolic over the whole period of the spectral response. Thin curves apply to individual interferometers **50a** and **50b**, whereas thick curves represent the sum of their group delays and dispersions available at output port **42**. In the top graphs, the spectral responses of the interferometers **50a** and **50b** are perfectly aligned. The sum of their group delays is then constant and a zero dispersion results. As the spectral shift between the interferometers increases, so does the slope of the resulting group delay and hence the dispersion. Inverting the spectral shift produces a negative dispersion rather than a positive one as shown in FIGURE 8. This figure also shows that an increase in dispersion comes along with a concomitant decrease in the useful bandwidth over which the desired dispersion is obtained. (The zones of negative dispersion in

FIGURE 8 are undesirable artifacts resulting form the superposition of neighboring periods of the spectral responses of the interferometers.)

The group delay variation over a spectral period of a single-cavity Gires-Tournois interferometer is not parabolic, as shown in FIGURE 3. The possibility of superposing many fiber Bragg gratings gives more flexibility in achieving the required positive and negative parabolic group delay variations illustrated in FIGURE 8 over a sizable fraction of the spectral period of each interferometer.

A bulk multi-cavity interferometer is more easily manufactured when the optical path length of each cavity is the same. The fabrication can then proceed as follows. A substrate of a suitable optical material is first polished to a thickness providing the desired FSR. It is then cut into pieces that are thin-film coated and assembled to form the multi-cavity interferometer. The equality in optical thickness for all cavities results in the group delay curve of the multi-cavity interferometer being symmetric over each period of the spectral response. This is the case for the multi-cavity interferometer disclosed in patent application [63]. This symmetry has an unfortunate consequence: a pair of interferometers with symmetric group delay curves produces a dispersion adjustment range that is centered around a zero dispersion level, as illustrated in FIGURE 8. All results obtained with this type of dispersion compensator that have been published to this day are consistent with this observation [4,5]. In order to center the dispersion adjustment range around a non-zero dispersion, it is necessary to introduce some asymmetry in the spectral response of one interferometer. This case is illustrated in FIGURE 9, where the group delay represented by thin solid curves in the left graphs is clearly not symmetric over a period of the spectral response. As seen in the top graphs, the dispersion takes a non-vanishing value when the spectral responses of the interferometers are perfectly aligned. A thermally-induced spectral shift between the interferometers results in a variation of the dispersion around this non-vanishing value. A bulk multi-cavity interferometer with an asymmetric group delay curve, and

thus with a different optical phase from cavity to cavity, will be much more difficult to fabricate. Fiber Bragg grating fabrication techniques are better suited for this task.

The vernier effect has been used to implement some dispersion slope compensation with a pair of multi-cavity interferometers of slightly different FSRs [4,5]. This approach is illustrated in FIGURE 10, where the group delay curves have slightly different periodicities. The first periods to the left of the graphs are perfectly aligned, so that dispersion over this channel vanishes. The increasing shift between the periods resulting from the difference in FSRs produces a dispersion that increases from channel to channel when moving to the right of the graphs. Shifting further the spectral response of one interferometer with regards to the other, by thermal means for example, adds the same dispersion to all channels without modifying the dispersion slope created by the difference in FSR, as illustrated in the middle and lower graphs in FIGURE 10. This approach has two disadvantages. Firstly, the dispersion slope is not proportional to the absolute dispersion level but remains constant as determined by the difference in FSRs of the two interferometers. This behavior does not match the evolution of the dispersion affecting an optical signal propagating along an optical fiber. The dispersion in each channel increases proportionally to the distance of propagation in the fiber, albeit at a possibly different rate from channel to channel. Under such conditions, it is clear that the difference in dispersion between two channels will be proportional to the dispersion level in each. Secondly, dispersion slope compensation through a vernier effect uses up some of the dispersion adjustment range afforded by the multi-cavity interferometers, as seen in FIGURE 10. This is so because the dispersion slope compensation and the thermally induced dispersion both result from a relative shift between periods of the spectral response of the interferometers, the allowed total shift being limited by the minimum fractional bandwidth of each channel over which the dispersion compensation is required.

The vernier approach can be implemented with fiber Bragg grating interferometers. However, fiber Bragg gratings offer a much better approach towards dispersion slope compensation. One can use a pair of multi-cavity interferometers made of fiber Bragg gratings, each grating (other than those with a high reflectivity) having a reflectivity that varies with the optical frequency. The spectral variation of the reflectivity of the gratings is designed in such a way that each interferometer still produces a dispersion that varies linearly over a sizable fraction of each period of its spectral response. However, the slope of the linearly varying dispersion of each interferometer varies from channel to channel. The dispersion of the pair of interferometers will thus vary linearly with the thermally induced spectral shift between them, as previously, but at a rate that will vary from channel to channel. This method will provide a dispersion slope compensation that is proportional to the dispersion levels in each channel. A properly designed pair of interferometers will actually be capable of compensating for all orders of dispersion. Moreover, the useful fractional bandwidth over which the dispersion compensation is achieved will be the same for all channels.

In conclusion, Fiber Bragg grating Gires-Tournois interferometers can be used for dispersion compensation. These interferometers avoid the birefringence limitations of ring cavities. They are compact and will likely be more robust than their bulk counterparts. Fiber Bragg grating fabrication techniques will make it easier to control the relative optical phases of cavities in multi-cavity interferometers. The spectral variation of the reflectivity of fiber Bragg gratings can also be controlled easily. This will allow the design and fabrication of devices capable of compensating for all orders of dispersion.

Although preferred embodiments of the present invention have been described in detail herein and illustrated in the accompanying drawings, it is to be understood that the invention is not limited to these precise embodiments and that

various changes and modifications may be effected therein without departing from the scope or spirit of the present invention.